From Sail to Soil – Getting Sailcraft Out of the Harbour on a Visit to One of Earth's Nearest Neighbours

Jan Thimo Grundmann(1,2), Waldemar Bauer(1,3), Jens Biele(11,12), Federico Cordero(14), Bernd Dachwald(15), Aaron D. Koch(1,4), Alexander Koncz(16,17), Christian Krause(11,13), Tobias Mikschl(19,20), Sergio Montenegro(19,21), Dominik Quantius(1,5), Michael Ruffer(19,22), Kaname Sasaki(1,6), Nicole Schmitz(16,18), Wolfgang Seboldt(23), Patric Seefeldt(1,7), Maciej Sznajder(1,8), Norbert Tóth(1,9), Elisabet Wejmo(1,10)

(1)DLR Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen – (2)+49-(0)421-24420-1107, jan.grundmann@dlr.de – (3)+49-(0)421-24420-1197, Waldemar.Bauer@dlr.de – (4)+49-(0)421-24420-1183, Aaron.Koch@dlr.de – (5)+49-(0)421-24420-1109, Dominik.Quantius@dlr.de – (6)+49-(0)421-24420-1150, Kaname.Sasaki@dlr.de – (7)+49-(0)421-24420-1609, patric.seefeldt@dlr.de – (8)+49-(0)421-24420-1623, maciej.sznajder@dlr.de – (9)+49-(0)421-24420-1186, Norbert.Toth@dlr.de – (10)+49-(0)421-24420-1107, Elisabet.Wejmo@dlr.de – (11)DLR Space Operations and Astronaut Training – MUSC, 51147 Köln, Germany – (12)+49-2203-601-4563, Jens.Biele@dlr.de – (13)+49-2203-601-3048, Christian.Krause@dlr.de – (14)Telespazio-VEGA, Darmstadt, Germany, federico.cordero@telespazio-vega.de – (15) Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany, +49-241-6009-52343 / -52854, dachwald@fh-aachen.de – (16)DLR Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin – (17)+49-(0)30 67055-575, Alexander.Koncz@dlr.de – (18)+49-(0)30 67055-456, Nicole.Schmitz@dlr.de – (19)Informatik 8, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany – (20)tobias.mikschl@uni-wuerzburg.de – (21)sergio.montenegro@uni-wuerzburg.de – (22)michael.ruffer@uni-wuerzburg.de – (23)Consultant to DLR Institute of Space Systems, nc-seboldwo@netcologne.de

IAA-PDC15-04-17

„go fly a sail every other year" – the GOSSAMER Roadmap

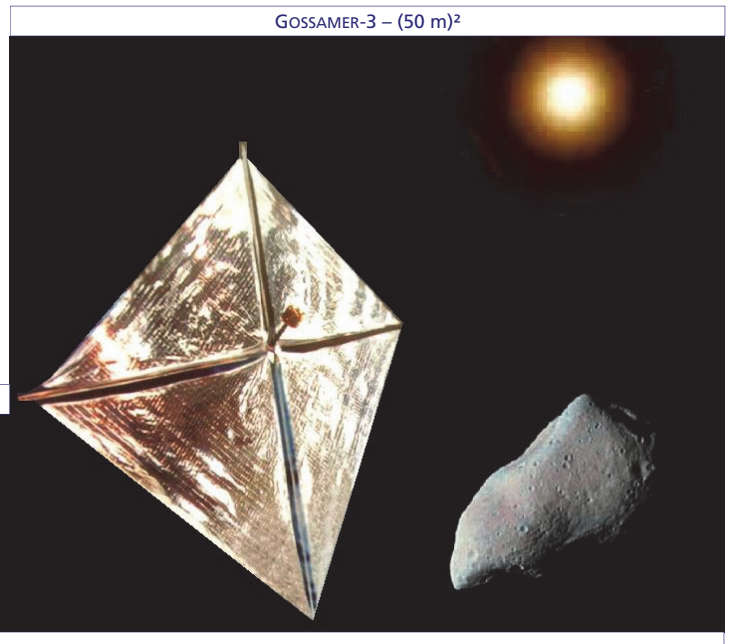
GOSSAMER-1
- very low Earth orbit, short-duration mission
- demonstrate fully controlled synchronized deployment

GOSSAMER-2
- low to medium altitude Earth orbit, safe disposal
- solar radiation pressure dominant non-gravitational force
- test several attitude controlled methods quantitatively

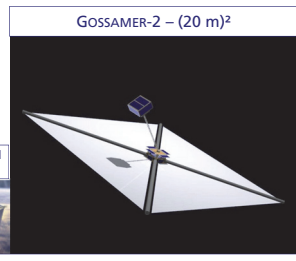
GOSSAMER-3
- high altitude Earth orbit, safe disposal above GEO
- demonstrate navigation, trajectory & timing control, and attitude control sufficient for initial science missions
- investigate sail side effects on science payloads

– note: service on this line is presently suspended indefinitely –

GOSSAMER-3 – (50 m)²



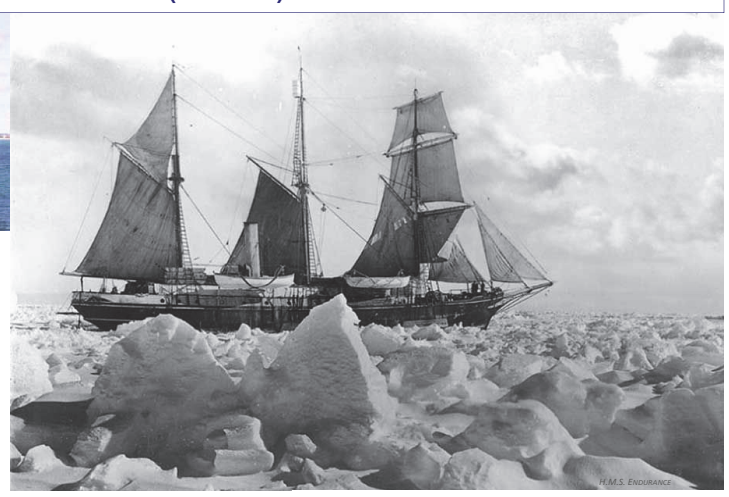
GOSSAMER-2 – (20 m)²



You are here

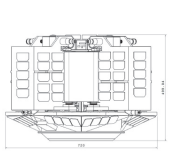
GOSSAMER-1 (5 m)²

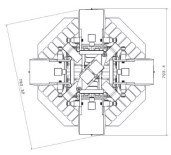
exploration vehicles (to scale)

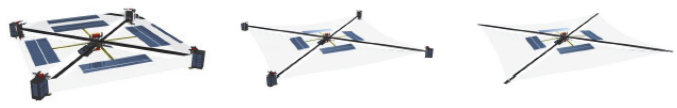


GOSSAMER-1 design

- free-flyer spacecraft designed for 'piggy-back' launch
- one Central Sailcraft Unit (CSCU), the sailcraft bus to fly on
- four autonomous Boom Sail Deployment Units (BSDU), jettisoned after deployment with all surplus equipment
- cubesat-based electronics in all five sub-spacecraft
- independent photovoltaic power supplies with charging network connecting all 5 units in stowed configuration
- radio network synchronized fully controlled deployment
- thin-film photovoltaics experiment on all sail quadrants
- multiple deployment observation cameras (red)







GOSSAMER-3 sail observation payload wish list

- wide-angle camera to observe sail deployment and long-term foil behaviour
- sensor to observe large area foil reflectivity ageing, e.g. by thermal equilibrium
- sensor to observe small-scale mechanisms of long-term foil ageing
- sensor to observe core spacecraft (bus electronics) electromagnetic signature
- sensor to observe illumination changes and Sun glints off the sail surface
- sensor to observe interaction of the sail with solar wind and geomagnetic field
- sensor to observe plasma, particle and energetic radiation environment
- sensor to register space debris and natural dust impacts on the sail foil

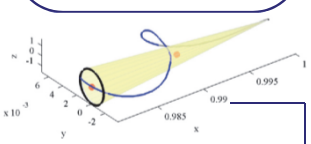
MASCOT Flight Spare/…s are almost always de-integrated to return science instruments to PIs science payload capabilities

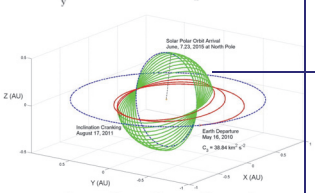
- ☑ CAM – 1 Mpixel Si-CMOS b/w (60°)² field of view camera, IRGB-LED illumination
- ☑ MARA – 6-band multispectral thermal infrared radiometer, 5…100 µm
- ☑ MicrOmega – hyperspectral near-IR microscope, self-illuminating 0.99…3.55 µm
- ☑ MAG – science-grade magnetometer, interplanetary to Earth surface field levels
- ☑ PEC, OPS (passive mode) – coarse Sun sensor, Optical Proximity Sensor receiver

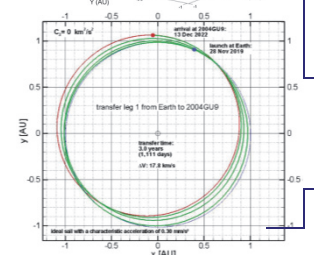
- ⊕ additional MAG instrument, 2 sensors spaced by ~1 m at 1 or 2 boom ends
- ⊕ e.g. Spherical EUV and Plasma Spectrometer (SEPS), 2 on opposite booms
- ⊕ e.g. acoustic pick-ups at rigging nodes, structural vibration accelerometers

first GOSSAMER science missions

Candidate mission types which are extremely difficult or currently impossible to fly using other methods of propulsion were identified by science communities and studied in three science working groups:
- Displaced L_1 solar storm early warning mission
- Solar Polar Orbiter
- multiple NEA rendezvous







EXERCISE – EXERCISE – EXERCISE – EXERCISE – EXERCISE

The GOSSAMER NEA rendezvous mission science working group study identified as a decisive key feature of solar sail propulsion the unique capability to change rendezvous targets *after* launch during cruise flight.

We welcome 2015 PDC !

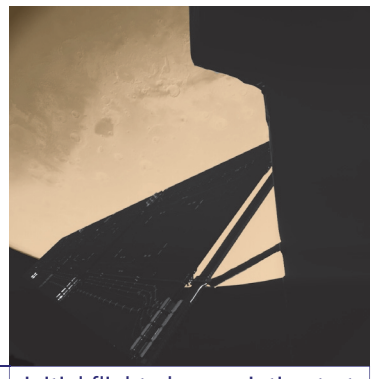
"go certify that sail" – a GOSSAMER-3 mission task-line in 101 small steps

minimum mission
- launch to any high Earth orbit presently in use
  - *if GTO launch*: chemical green propellant perigee raise burn to get above significant air drag and space debris
- deploy sail
- spiral up from launch orbit to comfortable sailing altitude
- multiple pointing and navigation tests
  - image Earth limb and Moon ; target specific locations on Earth and Moon ; Venus, bright stars…
- highly inclined passage through GEO region to minimize untracked space debris collision risk
  - keep inclination of e.g. NavSat orbit from piggy-back launch ⇔ build up inclination from Ariane GTO
- timed & targeted fly-by proof test : image a Chelyabinsk- to Tunguska-sized object on a well known trajectory in pan and slew attitude control modes
- spiral up further, at least to GEO upper graveyard altitude to safely stay above GEO indefinitely

expected or nominal mission
- spiral up to lunar distance
- opportunity-based distant lunar fly-by with timed & targeted observation accuracy proof test
- "all-up" navigation accuracy tests in the Earth-Moon system – get there on time & on target
- explore practical flying to and at the Earth-Moon Lagrange points
  - e.g. lunar L_2 far side relay ; look for Kordylewski dust clouds in L_4/L_5 using the ~2500 m² sail area as detector
- low-altitude lunar gravity-assist fly-by
  - may also be used in the following if the mission continues, imaging only by opportunity

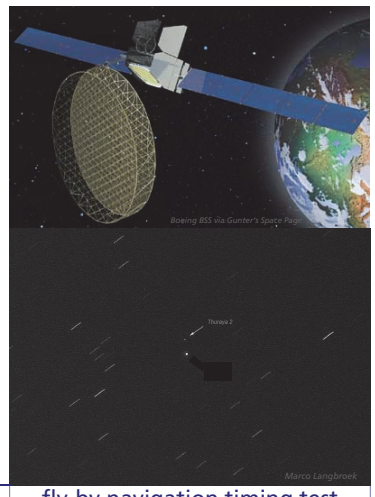
extended mission
- transfer to Earth-Sun L_2
  - flyby test: search & find a passive target on uncertain orbit, decommissioned L_2 spacecraft (PLANCK)
- transfer to Earth-Sun L_1
  - demonstrate Displaced-L_1 mode, if possible to equlibrium halo orbit ; study sail - solar wind interaction
- pole-sitter trial
  - modified sail-only trajectory, thus not always vertically above the pole but within line of sight

extended extended mission
- fly out to a co-orbital asteroid – low-inclination and eccentricity, large, slow rotator preferred
  - 2010 SO_{16} – 200…400 m, horseshoe librator, 14.5° inclination, 0.075 eccentricity
  - 2010 TK_7 – 300 m, L_4 tadpole librator, 20.9° inclination, 0.19 eccentricity
- rendezvous directly, or semi-fast flyby first and then loop back to return for rendezvous
- drop MASCOT FS, if suitable asteroid, and stay close enough to relay data until MASCOT EOL
- safe disposal of the lightened sailcraft
  - continue stationkeeping at the same NEA for long-term observation (magnetometer, star tracker imaging)
  - fly to another NEA within reach, e.g. small fast-rotator co-orbital on same L_4 /L_5 side but unsuitable for lander
  - beach sailcraft on an asteroid, if possible so that Sun glints are visible from Earth periodcally



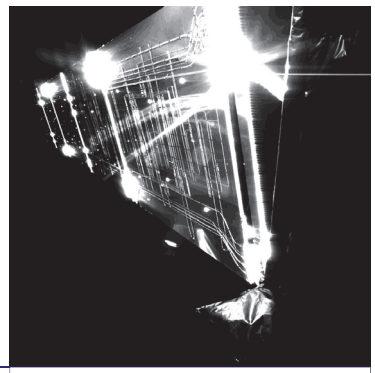
initial flight phase pointing test

PHILAE's view of Mars during ROSETTA's flyby on February 25th, 2007, taken at a distance of 1000 km – an example for early in-flight instrument pointing capability tests using the limb and albedo patterns with parts of the sail in the foreground imaged by the MASCOT FS CAM wide-angle *black-and-white* camera during the spiral-up & out of lower Earth orbit phase; also in later phases near the Moon.



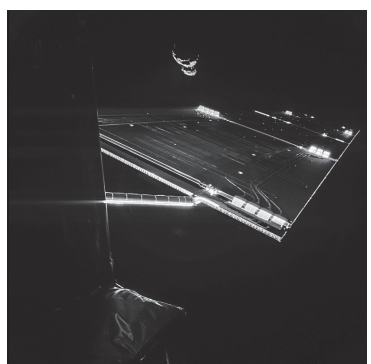
fly-by navigation timing test

The THURAYA-2 geostationary direct-to-satellite mobile phone service spacecraft with its Ø12 m dish antenna – a possible target among many for a combined test using the MASCOT FS CAM instrument for confirmation images of a 'moving dot' and/or 'tracked dot' (as above) during a targeted and timed fly-by of a 'Tunguskoid' size object. This and many other geostationary spacecraft are similar in size to ROSETTA which during its second Earth flyby on November 13th, 2007 was briefly designated as 2007 VN_{84} and by observed H = 26.3 mag estimated at a Ø 9…30 m.



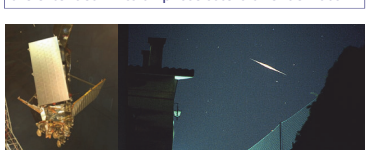
monitoring the sail foil

First Light image of PHILAE looking at the rear, shadowed radiator side of one of ROSETTA's 14 m long, 32 m² area photovoltaic panels in full sunlight – an example for High Dynamic Range photography using the HDR-capable MASCOT FS CAM instrument any time during the solar sail cruise phase.



turning into finals

67P/CHURYUMOV-GERASIMENKO as imaged by PHILAE along the rear, shadowed side of one of ROSETTA's fully illuminated photovoltaic panels – an example for photography of a low-albedo target object using the MASCOT FS CAM instrument e.g. during the extended² mission phase asteroid rendezvous.



farewell

IRIDIUM flare: 800 km distant, 1.6 m² reflector up to 50 times brighter than Venus. Sail flares at a close NEA would be stationary, detectable by telescope.